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Evolution of Sonar Survey Systems for Sea Floor Studies.

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ABSTRACT

Approximately 71% of our planet is covered with oceans. It is also known that oceans are the last frontiers for the mankind's survival and therefore it becomes pertinent that they are studied in great details. It has been found that the exploration of the oceans can be done more precisely using acoustics as one of the methods, as the acoustic waves can propagate over large distances and also using a broad spectrum of frequencies various issues of the ocean studies can be addressed more effectively than many of the other methods, both in terms resolution (using high frequency components) of measuring parameters and over large ranges (using low to very low frequency components). Currently with the technological advancement and improved computing algorithms, we have state of art systems for ocean exploration, which can provide information about the sea floor, sub-surface including ocean floor classification. These could be projected in 2-D and 3-D visualization to a great accuracy. Also available are acoustical methods wherein one can obtain an extremely important information about water column properties (both in terms of bio-information and physical properties), and has great importance as this water column is the medium for transmission of all kind of energies(acoustic for short, medium and long ranges and some time light source for exploration over a very short distance) that are used for exploration on the oceans. It will therefore be interesting to understand the progress of underwater acoustics from its very primitive stage, where acoustic transmission through water medium was used for first time to the present day highly complex but very advanced acoustic sea-floor surveying systems. It will also be interesting to know, with a very old maritime history of using seas for transportation, as to what were the methods used by early time seafarers to understand depths of the oceans they were sailing. It has taken almost a century in developing an acoustic system to arrive at the present day advancement. An attempt has been made to present a perspective of evolution and advancement in underwater acoustics and related electronic, material and computational advancement, starting from the early attempts to the modern day acoustic equipments

KEYWORDS: ***Sonar, acoustic, calibration, bathymetry***

Introduction

(The ultimate goal of a bathymetric survey is to produce a bathymetric map of an area surveyed with a certain geographical reference frame. These charts are of primary importance for navigation in navigational channels, river navigation, for vessel movements in harbour areas, for naval exercises and in the near shore coastal regions for vessels working in shallow water depths. The other important aspect of bathymetric observations is in conducting geological and geophysical exploratory type of surveys, which provide a vital information about morphological features of the sea-floor that is important in understanding tectonic behaviour of the floor and forms a primary evidence about major changes sea-floor has undergone and dynamics thereof. This data can provide a great insight in earth evolutionary processes to know continental shelf dynamics, canyon and seamount formations, riverine fans extending to large distances into ocean basins etc. Also the bathymetry data obtained for any area is very useful in gravity anomaly studies.

This article will mainly discuss about:

Historical importance of evolution in underwater acoustics and

Impact of advancement in technology, material and computational methods to arrive at present generation sea-floor surveying and mapping acoustics systems.

HISTORY OF SOUNDING TECHNIQUES[1],[8]:

The simplest and oldest means of bathymetric survey is the sounding pole. This technique involves using of a long straight pole to measure water depths – the method was effective, but limited in use to shallow water.

The sounding pole was replaced as a survey technique by the traditional lead-weighted line. Mariners conventionally took soundings in shallow water with a lead sinker on a rope or cable or fishing line primarily to locate navigational hazards and safe anchorages in near-shore zones and estuaries. The line was marked with knots or coloured ties at regular intervals. In the mid 1880's piano wire was used as replacement for the fishing line that allowed line with greater strength. This technique involved lowering a weighted-down rope or cable over the side of a ship, then measuring the length of the wet end when it reached the bottom. Inaccuracies occurred because of bending of the rope, caused by deflection from subsurface currents and ship movements. Until the 20th Century, the lead line was the only effective tool for deeper water bathymetric measurement. The main disadvantage of the lead-weighted line was that the survey vessel had to be stopped when measurements were made. Also X and Y (lat and long) positioning of the vessel had to be made manually and was time consuming.

In 1822, **Jean-Daniel Colladen**, a Swiss physicist/engineer and **Charles-Francois Sturm**, a mathematician, made an attempt to calculate the speed of sound in the waters of Lake Geneva, Switzerland using an underwater bell. In his experiment an underwater bell was struck simultaneously with ignition of gunpowder. The flash from the ignition was observed **10 miles away** and compared with the arrival of the sound from the bell underwater heard through a trumpet-like device in the water. In spite of these crude instruments, they managed to determine that the speed of sound under water was 1435 metres/second at 8° C water temperature, a figure that matches with what is known today. This led to other inventors experimenting with sonar. But took a long time of almost 90 years. When in 1906 Lewis Nixon created the first sonar listening device to detect icebergs.

1912 Robert Boyle creates a sonar device, and beats all other countries in doing so.

1917-1919 - World War I accelerates oceanic acoustic research as both the U.S. Navy and the Army Coast Artillery develop research programs to devise means to detect enemy submarines. 1915 Paul Langévin invented the first sonar device to detect enemy submarines in World War One. Although this sonar did not send out signals, it could still detect submarines by using the piezoelectric properties of

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the quartz. This sent out electricity that detected objects.

1918 Great Britain and the United States create the first sonars to send out signals to detect enemy submarines.

After their use for detection of coast and other ships, it was realised that, if sonar device was pointed down to sea floor, it would be possible to accurately measure depth. The traditional technique of sounding was now replaced in 1920's by echo sounding, in which a sound pulse would travels from the ship to the ocean floor, get reflected and returns. By measuring the time elapsed between pulse tranmission and reception, a record of seafloor topography along the ship's track can be registered.

1922 - The USS *Stewart* runs a line of soundings across the Atlantic Ocean using an acoustic echo sounder devised by Dr. Harvey Hayes, a U.S. Navy scientist. The French also run an acoustic sounding line from Marseilles to Phillipeville, Algeria, for a submarine cable survey.

1941-1945 - During World War II, electronic navigation systems are developed for precision bombing, including the gee system, which C&GS hydrographers adapt and rename Shoran. In 1945 the C&GS conducts its first hydrographic surveys using Shoran. Other inventions from this period pertinent to ocean exploration include deep-ocean camera systems, early magnetometers, sidescan sonar instruments, and early technology for guiding ROVs (remotely operated vehicles).1940 Sonars were installed along the coast of southern Britain to detect enemy fighters and allow Britain to concentrate their defense on that side.

Later it was also found that if some more energy was put into the ping you could get echoes from the sediment layers and rocks below the bottom profile, and this was called "Sub-Bottom profile" By recording the amplitude of the backscatter energy as a function of time and making some assumptions about sound velocity in the water (1500 m/sec) and the rocks (faster than 1500 m/sec), marine geologists could convert this data into water depth and rock layer thickness. By pinging continuously, driving the boat in straight lines, and laying all the ping records next to each other, they got an image, which looked like a vertical profile through the water column and sub-bottom. Dark reflectors correspond to scattered energy from point scatterers or layer transitions, termed changes in acoustic impedance (density x sound velocity in the upper layer divided by the same for the lower layer). In the 1950's improvements in transducer technology and timing accuracy introduced precision depth sounders (PDRs), whose beamwidth was 30-60°, and which only made it possible to create large-scale maps of the seabed.

1961 - Scripps Institution of Oceanography began development of the Deep Tow System which was the forerunner of all remotely-operated and unmanned oceanographic systems.

Some of the developments in the early 1960,s introduced bases for multi-beam echosounder. One of the important results was, the time for beam stabilization of single-beam depth sounding, to compensate the ship movement. To archive this result, electronic stabilization scheme was introduced- thereby removing the mechanical stabilization and improvising the system reliability. D.G. Tucker improved single-beam systems further, by using interferometric technique and electronic sector scanning of a single-beam by rapidly changing the phase delay of each transducer element.

The need for area coverage was partly covered by parallel sounding method consisting of using several echosounder at the same time, mounted on long rods extending out from the ship. This method was impractical, especially in rough seas. A similar method was tried with towed bodies. The more advanced parallel sounding method used was, where several ships navigate in parallel courses, each covering a separate area, overlapping the area covered by its neighbour ship.

1963- The first operational multibeam sounding system was installed on the USNS Compass Island.

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This system, and other multibeam sounding systems that have evolved since, observe a number of soundings to the left and right of a ship's head as well as vertically allowing the development of a relatively accurate map of the seafloor as the ship proceeds on a survey line.

The first multi-beam echosounder for shallow water surveys BO'SUN, formed 21 beams and had a coverage of 2.6 times water depth, operational frequency of 36 Khz and maximum survey depth of 800 meter.

Starting in the 1970s, companies such as General Instrument (now SeaBeam Instruments, part of L3 Klein) in the United States, Krupp Atlas (now Teledyne Atlas) and Elac Nautik (now part of L3 Communications) in Germany, Simrad (now Kongsberg Maritime) in Norway and RESON in Denmark developed systems that could be mounted to the hull of large ships, and then on the small boats (as technologies improved and operating frequencies increased).

These early-developed systems were far more limited in terms of swath coverage, map generation capability, computation and handling of data, corrections with regards to dynamics of the platform motion parameters. The first generation system provided a swath width of 45° (coverage up to 75% of water depth) with 16 beams. The first commercial multibeam was known as the SeaBeam Classic and was put in service in May 1977. The manufacturer later developed newer systems such as the SeaBeam 2000 and the SeaBeam 2112 in the late 1980s and SeaBeam 3012 in 2003.

As technology improved in the 1980s and 1990s, higher-frequency systems suitable for high-resolution mapping in shallow water were developed, and such systems are widely used for shallow-water hydrographical surveying in support of navigational charting. Multibeam echosounders are also commonly used for geological and oceanographic research, and since the 1990s for offshore oil and gas exploration and seafloor cable routing.

In 1989, Atlas Electronics (Bremen, Germany) installed a second-generation deep-sea multibeam called Hydrosweep DS on the German research vessel Meteor. The Hydrosweep DS (HS-DS) produced up to 59 beams across a 90-degree swath, which was a vast improvement and was inherently ice-strengthened. Early HS-DS systems were installed on the RV *Meteor (1986)* (Germany), the RV *Polarstern* (Germany), the RV *Maurice Ewing* (US) and the ORV *Sagar Kanya* (India) in 1989 and 1990 and subsequently on a number of other vessels including the RV *Thomas G. Thompson* (US) and RV *Hakurei Maru* (Japan).

Today's equipments with VLSI technologies have proportionally reduced in size, and capabilities have increased in terms of resolution, coverage, data handling, storage.

TECHNOLOGY

An overview of first generation of Multibeam sonar systems:

Any echo-sounding system generally has 4 main components, namely i) Transmitter, ii) Transducers for transmitting and receiving acoustic waves, iii) Receiver carrying out necessary signal conditioning and lastly iv) a display and data storage/logging system. A multibeam sonar also uses this basic concept, but differs vastly from simple single beam echosounders.

In case of a single beam echosounder, the beam is transmitted directly below the transducer, and the depth is determined based on the total travel time taken by sound wave t from transmission- to reflection from seafloor - to finally received by the receiving transducer. This provides depth directly below the transducer location only. In case of a multibeam sonar, we are trying to get a wider insonification of the seafloor, by transmitting a fan shaped beam on the seafloor. This beam is narrow in the along track and wider in across track direction to cover desired bottom area.

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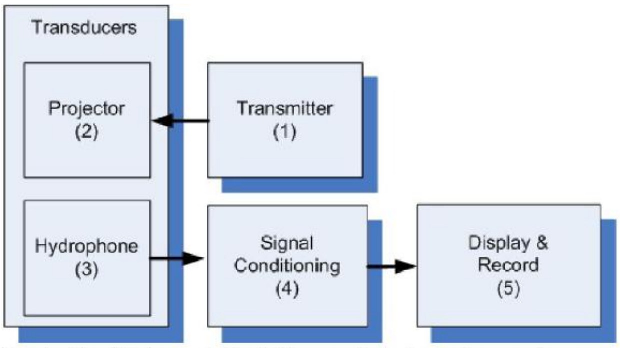

Fig.1 Block diagram of a multibeam sonar system.[6]

The coverage depends on the frequency of operation, larger for low to medium frequencies and narrower for high frequency signals. For deep water systems, it is difficult to generate a single fan shaped beam that would cover a desired bottom area, as the energy contained by the outer beam sectors will dissipate very fast and no meaningful returns from the reflected signal can be expected in such case. Therefore in this case the beam is transmitted in different athwartships directions by electronically steering the signal, either from port to starboard direction or the other way. The time gap in each burst of transmission is very short. This is necessary because, the ship is in forward motion and a delayed transmission may cover a different area, if the time gap is not maintained short. Also there will be a slight overlap between each angular sector ensonification to compensate for any roll during the transmission. Details of the transmit and receive signals is shown in the figure below:[5]

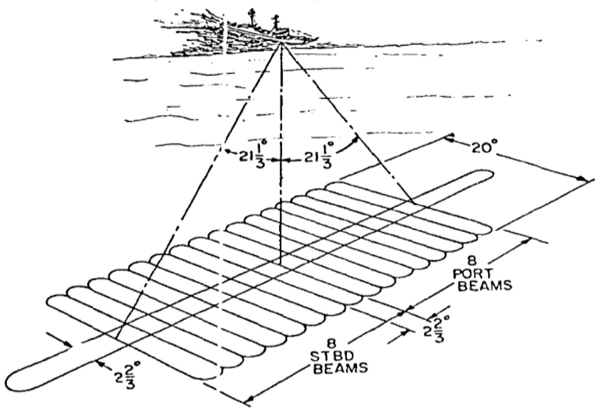

Fig.2 Transmit and receive signals of multi-beam sonar

Developments in Signal conditioning:

Early systems that came in to existence, when the developments in electronic components was in its early stage[9]. The system design therefore needed a careful selection and application existing components. By this time in late 70s, bit slice processors had come in to play, which allowed 4 bit digitization of analog signals. As the range of data from the returned signals in time domain was very large, a technique of splitting the signals in time domain was necessary. This needed a very careful design aspect, to capture entire signal without loosing any of the return reflected signal from seafloor. A schematic of basic A/D conversion of reflected signals is shown in the figure below:

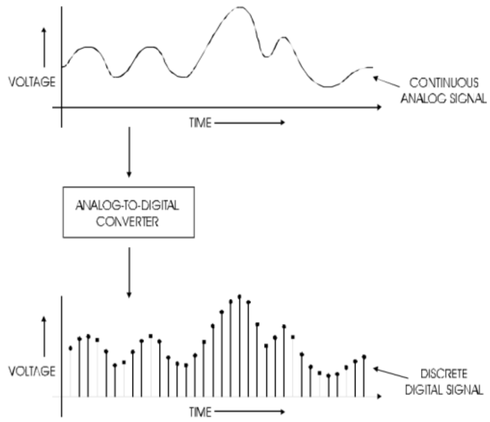

Fig.3 Analog to digital conversion of hydrophone data

The signal processing due to limitation in the required electronics development that time, was very complex in nature. Intel D 8088 microprocessor was used as central processing Unit, where the CPU could process 16 bit information internally, but could output only 8 bit data. The address range in these cases was 20bits for memory access and 16 bit for peripheral access. The data memory comprised of 64KB of dynamic RAM. Following diagram shows a general structure of one of the display control CPUs:

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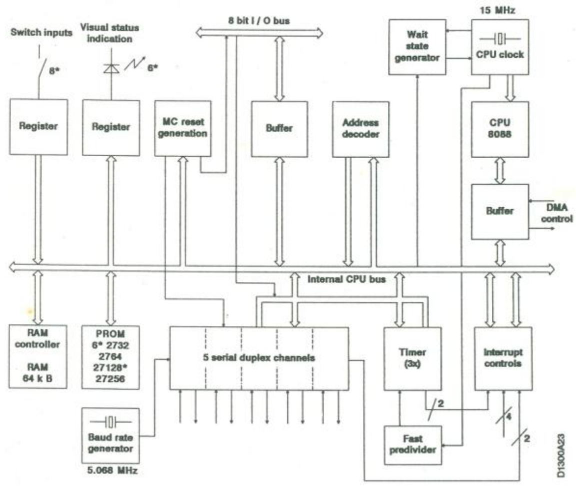

Fig.4 Block diagram of one of the CPU assemblies in older systems[2]

The signal processing in the older systems contained 72 TVC controlled amplifiers, a beamformer module which included memory mapped architecture through pre-programmed delay lines to generate 59 received beams OR depth values, followed by a PFB filter module with filter and control functions embedded in to it which generated optimally filtered information of each PFB and send this information for further processing. The control unit in this module also received position data, roll, pitch and heave data. Entire signal flow in the system was controlled by a control processor located in the PFB module. This module drives and controls all the electronics in the signal processing unit. The functionality of a beamformer module related to 72 amplified signals from transducer staves , which pass through a number of delay lines for getting signals from desired directions. This is achieved by adding signals in correct phase and from correct staves. As 59 beams are generated by the system to get 59 depth values, there are 59 directions of steering received signal with 59*72 delay combinations. A block diagram of a PFB filter is shown below.

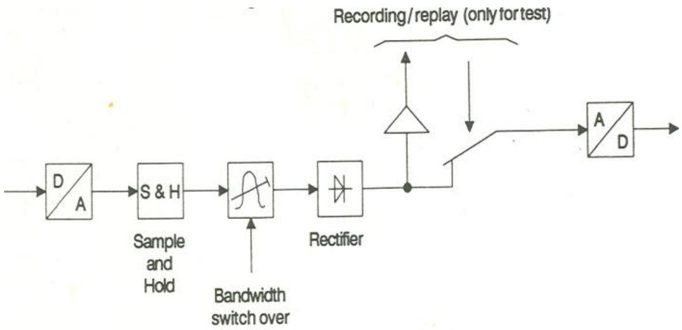

Fig.5 A Pre-Formed Beam (PFB) filter illustration in older systems[2]

A block diagram of a PFB module showing complexity of signals is shown below:

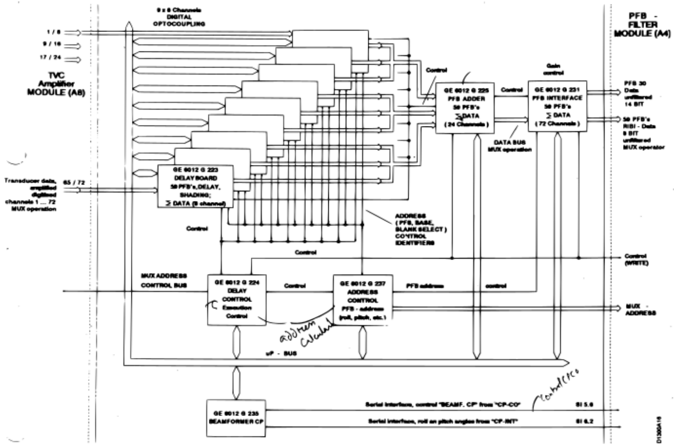

Fig. 6 Block diagram of a PFB module[2]

For the gain control of all 72 preamplifiers, they are grouped in 9 groups of 8 channels, connected in parallel. The overall dynamic gain range between -6 dB to +/- 70dB was controlled by a separate group of microprocessor assemblies. For this there are 8 delay board assemblies, which handle intake of TVC channel data, applying a weighting factor with reference to shading coefficients and a partial sum formation with regards to expected receiving direction. Forming a preformed beam information was a very complex process of generating a buffered memory space , where the summing of signals takes place. These signals were then transferred to a PFB interface which actually involves echo formation process. A diagram of a bottom echo control module is shown below:

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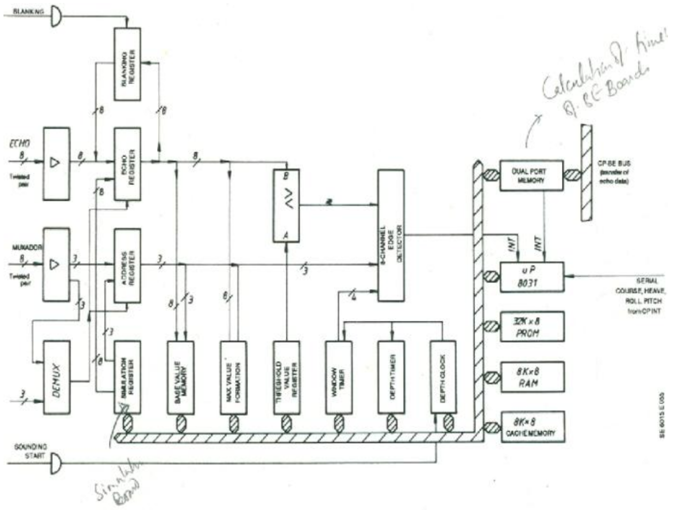

Fig.7 Block diagram of bottom echo control module[2]

In addition to the main sonar system components, the other peripheral systems required for a multibeam swath bathymetry systems are the positioning system, attitude monitoring system and the data storage systems.

In the initial systems used for the positioning of a survey vessel were the radio ranging systems, wherein these systems comprised of a radio transceiver on a moving vessel and three base stations placed at suitable line-of-sight locations on land. On command from the mobile main system, the land systems will send a reply signal. Each land system had a unique identification code. Based on the time taken by the radio signals received by the mobile system, the position of the vessel was fixed by triangulation method. In this the distance from each base station was computed by knowing travel time of received signals. But these systems could be used over a limited distance from the land. For deep water positioning satellite based navigation systems were designed at a later stage in early 80s or late 70s. There were 3 to maximum 6 satellites in the range of the satellite receiver placed on board a vessel. The lacuna of this system was, these signals were available only during the satellite passes over the vessel. At other times the position was based on dead-reckoning logic, where the heading and speed data was considered to determine the ship's position considering that vessel was moving in a straight line. But in a very dynamic ocean atmospheric condition, it was not possible to get exact location. These data were refined by using Kalman filter algorithms.

In case of motion sensors(attitude monitoring sensors were also not digital but they used to provide synchro outputs, which needed to be retrieved using 20mA current loop. Also the heave sensors were similar analog type.

Even the data storage was on tape drives, on which data was stored in binary format. The data needed to be read using a separate software.

Looking at the above details, one can imagine the complexity of electronics involved in designing such systems. All the three major systems developed in late 70s and early 80s, had similar electronics functionalities, with little differences. The most important part is the coverage of the seafloor or the bottom foot print was limited to a total angle of insonification to 90°. This means, these systems were capable of covering a range in the across the ship direction of twice the water depth.

Present Generation Multibeam Sonars:

The main aim of any multibeam sonar is to provide an accurate depth information which is related to a geo-referenced position of the installed transducers. As is known, in the wide angle transmissions used in these sonars, the signals undergo refraction effects, which change their direction of transmission as well as the path length traversed by the transmitted signal and therefore the received signal as well. This will affect the depth determination, as the signals may arrive at the face of transducers either early or later, due to bending of sonar signal rays towards or away from normal owing to oblique incidence on the seafloor. As the vessel undergoes roll pitch, roll and heave motions, the signals, both transmitted and received, will undergo further changes, leading to inaccurate depth measurements. Though the changes due to these effects were applied in the old generations, being analog signal form motion sensors, the accuracy of these application was not up

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to the mark, as the digitizers also had limitations. The water column effects due to refraction of signals, have a large effect on the accuracy of the depth measurement. Therefore these changes in the water column need to be applied carefully. In the present generation systems, sound velocity profilers (SVP), which are very accurate are available. A sound velocity profile is obtained in the survey area and this is applied to the signals received from oblique angles. Also in order to control the direction of transmission, there is need of knowing the sound velocity at the face of transducers, to properly direct the transmit signals, with reference to attitude (roll & pitch of the vessel) data received from the motion sensor. Now the keel mounted smaller SVP sensors are available and provide necessary direction corrections to the transmit signals[3].

Figure 8 shows an overview of present generation system:

The system diagram shows both acquisition and post processing systems. The entire electronics for control, internal signal processing and connectivity to output devices is contained in the ICU, AEU and DEU units as three small cabinets. The entire system interconnectivity is built around local Ethernet network, which enable fast transfer of large volume of data within different processors and stages of signal processors. In the older systems, there were total 8 number of full height cabinets. In this navigation server plays a crucial role, as it integrates DGPS and motion sensors data together and provides this information not only to the deep-sea multibeam system, but also to all other systems installed on board the ship. The helmsman display provides navigational aid to the navigating officers to take the vessel on the desired survey track.

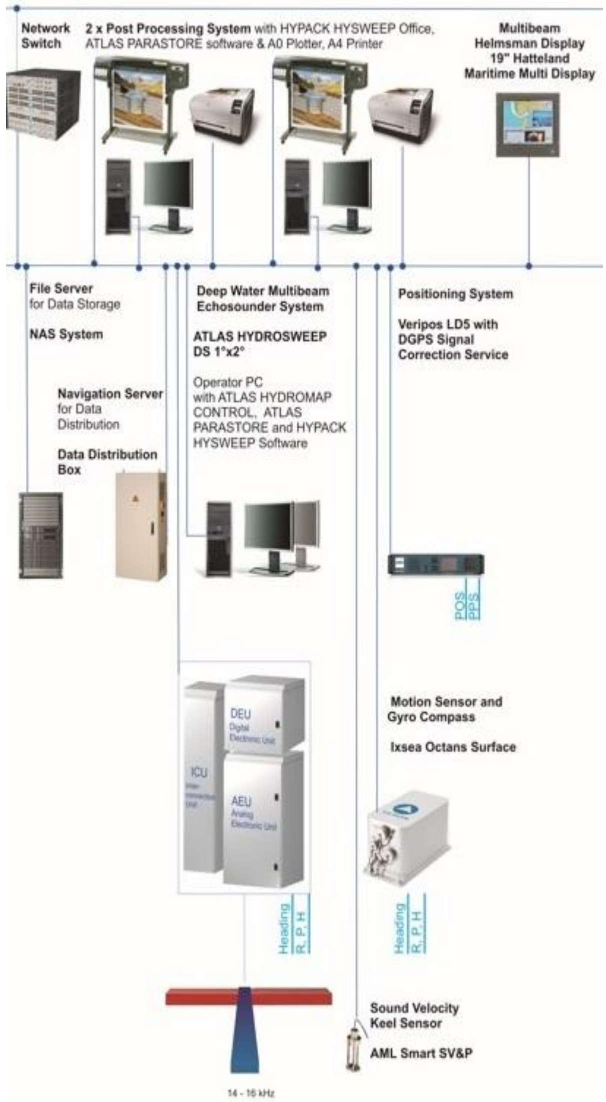

Fig.8 Deepwater Multibeam system overall configuration.[3]

Earlier calibration of the systems to arrive at installation parameters of roll, pitch offsets was difficult, which reduced overall accuracy of the depth measurements, as very complex computing of the received data, with all the attitude corrections applied, is required[4]. This is now possible with large volume of data received being computed with high speed and large dynamic memory systems available. Following figures (9,10,11,12,13) give an overview of the calibration process implemented to obtain installation offset parameters.

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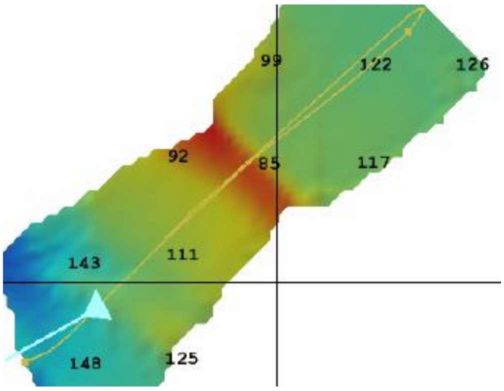

Fig.9 Roll calibration procedure

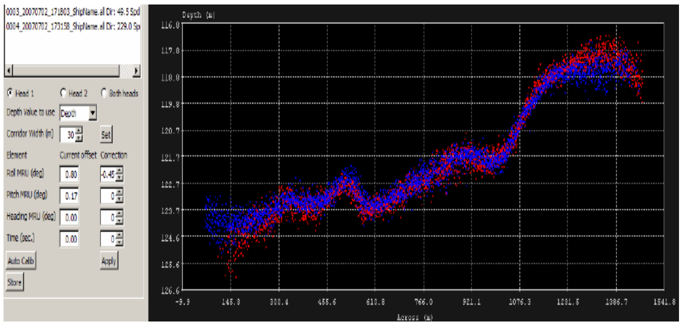

Fig.12 Data after applying a roll bias correction of -0.45°

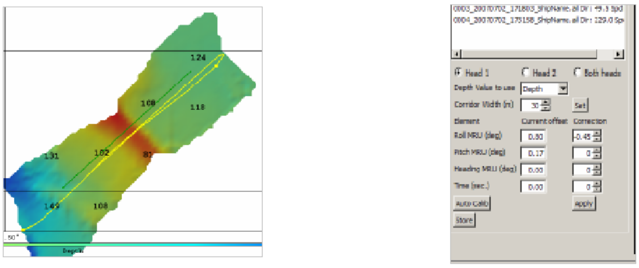

Fig.10 Pitch and time offset calibration procedure

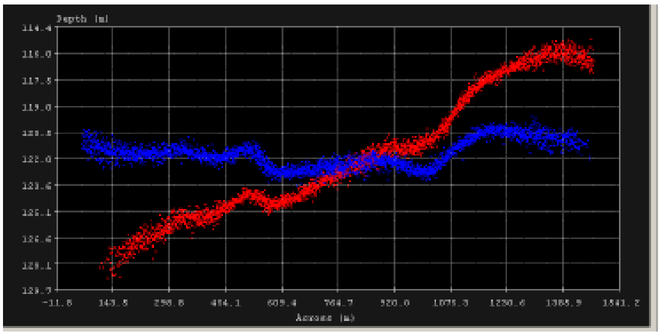

Fig.11 Data as observed before applying roll correction

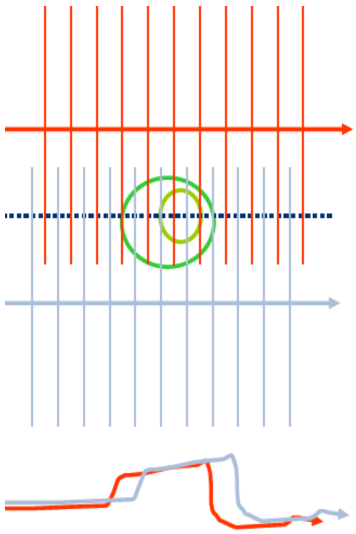

Fig.13 Heading calibration procedure

On completion of data collection for calibration of roll, pitch, heading bias computation, the computed offsets are fed in to the system as installation parameters. The are shown in following figure:

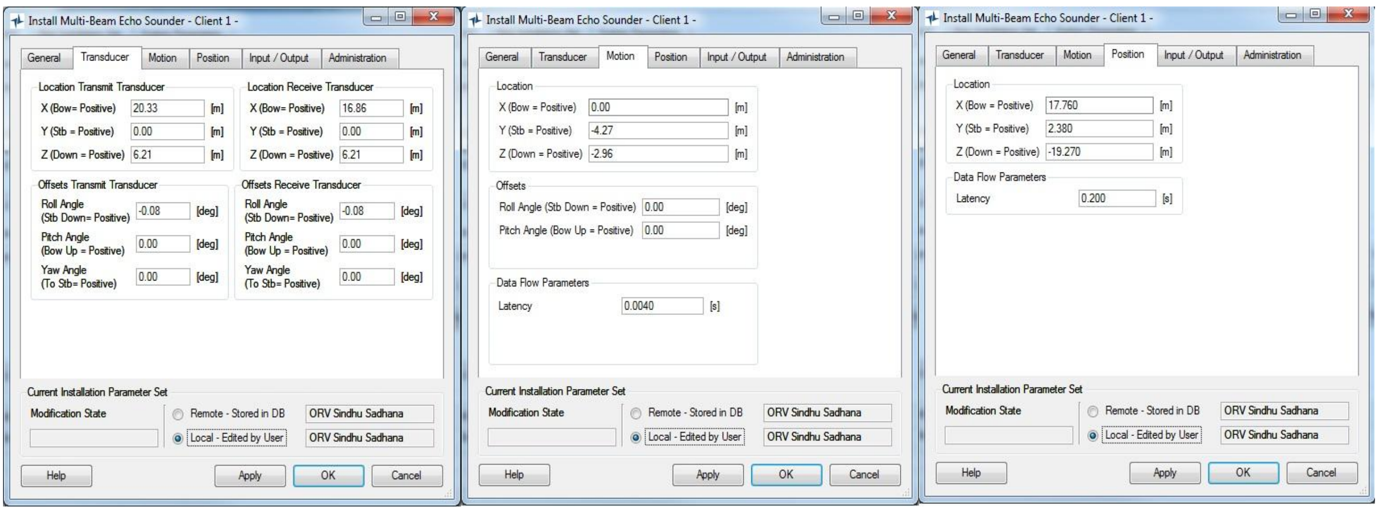

Fig.14 Installation parameter after roll, pitch, heading calibration

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The present generation navigation systems provide very high accuracy data for the geo-referencing of the bathymetry data. Now more than 12 satellites are available at any time to get continuous update of the position of vessel and any further dynamic corrections are possible through satellite correction signals. So, even in the deep sea regions, which are more than 1000 km away, we can get an accuracy of better than+/- 2 meters.

Present generation motion sensors are digital and FOG (fibre optic gyro) based, which provide a roll and pitch accuracy of better than 0.001° at any given time.

With huge development in the electronics, the processor speeds have increased enormously. Also the digitization of the data during the pre-processing or intermittent stages of signal conditioning, has reached to a level of 24 bits or better. This greatly helps during beam forming stage to generate very sharply defined beams. In the older systems, the maximum number of depth points that a system could provide were limited a maximum number of 59. With virtual beam forming process available now for the in-between hard beams, the present generation can provide a total of 960 or more number of beams. Also in older systems, the transmission was limited to a fan of maximum 90°. With improvement in the transducer systems and the related electronics, one can transmit up to 150° of beam width in case of deep water systems and about 170° of beam width for shallow water systems. This has increased the coverage sea floor per ping of transmission tremendously. This means that one can get about 5 times the depth of bottom coverage compared 2 times water depth in case of older generation systems. This has also resulted in the survey speeds, covering large areas in short time. For example in systems with 5 times water depth coverage, in a water depth of 2000 meters, one can get a swath width of 10000 meters. Therefore the present generation systems generate a large volume of bathymetry data with very high resolution.

The post-processing of the data in the older system had limitations due to slow computers. In the present generation systems very large volume data can be post-processed with greater ease and better accuracy[7]. The presentation of bathymetry maps in 2D and 3D projections is easily possible now. Following figure 15, shows a 3D view of processed data.

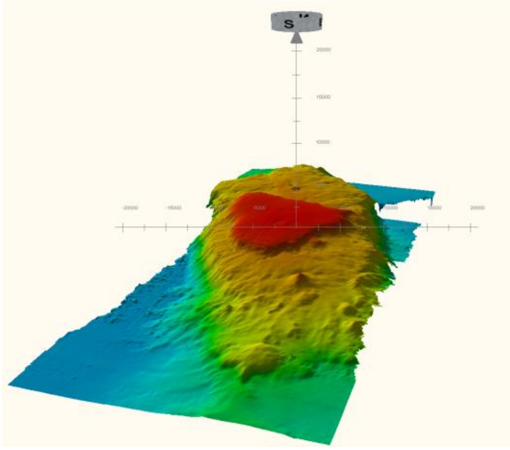

Fig.15 A processed 3D view of a sea mount feature surveyed during one of the scientific cruise.

Conclusion

Present generation sonar systems have evolved from the pole measurement – weighted line. The depth records that were available line scan printer records, which needed to be digitised, taking lot of effort and time, for any further post-processing, are now available in digital formats and can be exported to different platforms, processed and statistical data can be generated/compared. At the same time lot of constraints were addressed during the development era. Some of the constraints were, high resolution signal processing, better visualisation of the online data for monitoring, refraction related problems due to varying sound velocity, vessels attitude (roll, pitch and heave), transducer sizes.

Acknowledgment

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